THE DEPTH OF FIELD OF THE HUMAN EYE

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CONTENTS

PREFACE

The work presented in this thesis was completed in 1955 and published in OPTICA ACTA, 4, 157 to 164, in 1957. It is part of a general investigation into the nature of the stimulus which activates the accommodation response system of the eye.

However, this thesis is complete in itself as a contribution to the elucidation of the factors affecting the depth of focus of the eye. The specific question asked is:-

> What factors, peculiar to the human eye, modify the current estimations of the depth of focus based on geometric or wave theory optics?

The technique developed to investigate this question is a simple one, although it is precise and experimentally versatile. The results obtained are clear cut and lead to definitive conclusions.

At the end of the thesis two brief published summaries of work at present in progress are appendaged to indicate how the work presented here integrates with future developments.

INTRODUCTION

If the eye is focused for a given distance, then an object either nearer or farther away will produce a blurred image on the retina. Within a certain range, called the depth of field, the observer is unable to detect this blurring. It follows that any object within this range will be perceived with maximum visual acuity. The depth of focus is the equivalent range in the image plane, although this term is often used when referring to the depth of field in the object plane.

Many textbooks dealing with physiological optics contain tables giving the depth of field of the human eye. These tables are constructed by calculation based on the principles of geometric optics. For example, Campbell and Weir (1953) published such a table basing their calculation on the assumption that the observer can just detect blurring that subtends 1 minute of visual angle. The table is given below:-

Table 1.

Pupil diameter in mm.	Depth of field in dioptres.	Range of focus (cm) when focused on:- Infinity	100	50	25
1	± 0.29	Inf. to 350	60	15	3.6
2	± 0.15	Inf. to 700	30	7.5	1.8
4	± 0.075	Inf. to 1,400	15	3.8	0.9
8	± 0.038	Inf. to 2,800	7.5	1.9	0.5

It can be seen from table 1 that the depth of field varies inversely as the pupil diameter and approximately directly as the square of the distance focused. Similar tables have been published, although a value other than 1 minute of arc may have been chosen as the basis of the calculation.

The range of values chosen by different authors may readily be seen by inspecting table 2.

Table 2.

Author	Depth of focus with 2 mm pupil in dioptres.	Hyperfocal distance in metres.
Adler (1950)	± 0.067	15
Von Bahr (1952)	± 0.15	6.7
Campbell & Weir (1953)	± 0.15	6.7
Davson (1949)	± 0.25+	4
Emsley (1952)	± 0.09	11.1
Le Grand (1952)	± 0.15	6.7
Hartridge (1952)	± 0.063	16
Helmholtz (1909)	± 0.083+	12
Present investigation	± 0.43	2.3

+Pupil size not stated.

It is clear that there is a considerable difference of opinion about the amount of blurring that the observer can detect between these authors. Furthermore, all of them have assumed that the eye is a perfect optical instrument without aberrations. But the eye has many aberrations, some of them of considerable magnitude, and the resulting caustic at the retina is complex. This makes an accurate calculation of the depth of field so formidable that even Gullstrand (1909) abstained from attempting its solution. It is therefore surprising that no attempt has been made to verify experimentally if the computed values are correct for the normal observer. Although not bearing directly on the problem there are a number of clinical reports recording that clear vision may be present over a considerable range in the aphakic or cycloplegic eye. Brickeley and Ogle (1953) have recently reviewed the clinical literature and also have measured the depth of field of 100 subjects under homatropine-cocaine cycloplegia.

The determination of an absolute value for the depth of field must depend upon a definition of visual acuity and such a definition must involve arbitrary standards of measurement and target design. Thus, the existence of an absolute depth of field is problematical. The experiments here described have been designed not to determine the magnitude of the depth of field accurately under all visual conditions but to establish what factors peculiar to the eye modify any treatment of the subject based on geometric or wave theory optics.

METHODS

A diagram of the apparatus used is shown in Figure 1, although it is not drawn to scale.

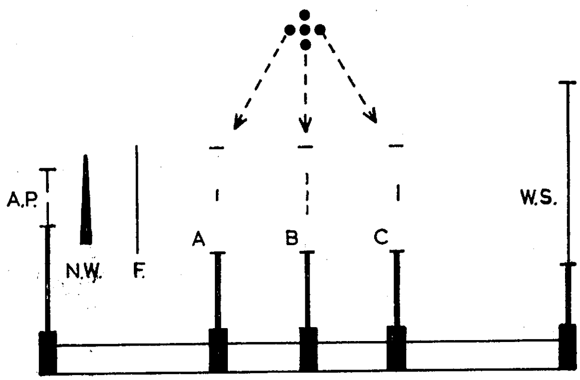

FIG. 1. — Diagram of the apparatus. Not to scale. A. P. — artificial pupil. N. W. — neutral wedge. F. — colour filter.
A, B and C — glass plates carrying the target spots shown above the diagram. W. S. — white screen floodlit to 5,000 mL.

The equipment was mounted on a standard 1 metre optical bench to permit easy adjustment of the components. The subject's head was steadied by means of a chin and forehead rest and one eye was centred on the artificial pupil (A.P.) placed as close to the eye as possible. The other eye was covered. If the subject was ametropic he wore his correction. The subject could then view a white screen (W.S.) placed at the far end of the bench through three glass plates A, B and C. The screen consisted of a layer of magnesium oxide deposited on an aluminised mirror that was evenly lit to a luminance of 5,000 mL with two floodlights of colour temperature 3,000° Kelvin. The middle glass plate (B) carried a vertical row of three discs seen dark against the dark background. Plate A carried a single disc situated so that it appeared to the left of the vertical row and plate C carried a similar disc displaced to the right of the row. The size of each disc was adjusted so that it subtended an angle of 10' at the eye and each was placed about 20' from its neighbour (see upper portion of figure 1). A square stop surrounded the targets, each side of which subtended 6°. These glass plates were mounted on optical saddles riding on the bench. Plate B was fixed at 50 cm from the eye. Plates A and C were freely moveable along the bench and their position could be determined from a scale attached to the bench.

To determine the depth of field, the subject was asked to fix and accommodate on the middle spot of the vertical row on plate B. Plates A and C carrying the near and far spots were then moved separately towards plate B until they appeared in sharp focus. Judgement of sharp focus was greatly facilitated by comparing the appearance of the spots with the upper and lower spots on plate B known to be in sharp focus. Subjects were permitted to glance quickly from one spot to another to ensure that each had an identical appearance. The depth of field could then be determined by measuring the separation of plates A and C. This method has the advantage that accurate accommodation on the target at 50 cm is unnecessary. As long as sufficient accommodation is exerted to bring the near point of the depth of field closer than about 45 cm it will be detected by plate A. After a short training period an intelligent subject can obtain readings differing only by 0.02 dioptres from each other. Observations are fatiguing and a brief rest period is required after each measurement.

The luminance of the test field was adjusted by means of a neutral density wedge (N.W.), situated close to the artificial pupil. To vary the contrast of the test spots against the background, each plate was separately illuminated with a small lamp fitted with a condensing lens. The beam of light from these lamps was focused on the spots which consisted of a spot of white paint. The lamps were attached to the optical saddles sothat they moved along the bench with the saddles. Luminance was measured with an S.E.I. photometer (Ilford) and this in turn was checked at frequent intervals against a standard lamp calibrated by the National Physical Laboratory.

The hue of the test field was altered by means of Ilford spectrum filters placed at position F on the bench. To obtain a field of different hue but of the same brightness a small flicker photometer was placed on the bench and the neutral wedge was used to adjust the intensity of the coloured field. Matches were made with a circular field subtending 2° at a luminance of 1 mL.

Mydriasis was achieved without interfering appreciably with accommodation by instilling 1% aqueous solution of p-hydroxyamphetamine hydrobromide (Paredrine hydrochloride, Parke Davis) into the conjunctival sac at 5 minute intervals until the pupil was suitably dilated.

The chromatic difference of focus of the eye, after homatropine mydriasis, was measured by placing a +2 dioptre lens before the eye with a 3 mm artificial pupil and measuring the far point of blurring with each of the spectrum filters in position.

The vernier visual acuity was determined by modifying a spectrometer similar to that described by Wright (1946). The exit slit of the spectrometer was replaced by an aperture of 2 mm diameter through which the observer viewed a vernier test object 50 cm from the eye against a circular coloured background 2° in diameter. Visual acuity was measured at steps of 10 mμ from 430 to 710 mμ at a luminance of 1 mL. The luminance of the coloured field was adjusted to abolish flicker when matched against a white field of 1 mL.

The chromatic difference of focus of the eye was corrected by placing an achromatizing lens immediately behind the 2mm viewing aperture close to the eye. The lens was kindly lent by Professor W. D. Wright and is identical to that described by Thomson and Wright (1947).

RESULTS

In this thesis the magnitude of the depth of field is expressed in two ways to simplify presentation of the results. The values are given either as ± half the total depth of field in dioptres, or as the hyperfocal distance in metres which is the reciprocal of half the depth of field expressed in dioptres.

The effect of luminosity on the depth of field.

The detection of out-of-focus blurring should depend upon the resolving power of the retinal receptors. Thus any factor, such as luminosity, which alters retinal form discrimination could affect the threshold for blur detection.

The effect of varying the luminosity of the test field on the determination of the depth of fiela with a 2 mm diameter pupil is shown in figure 2.

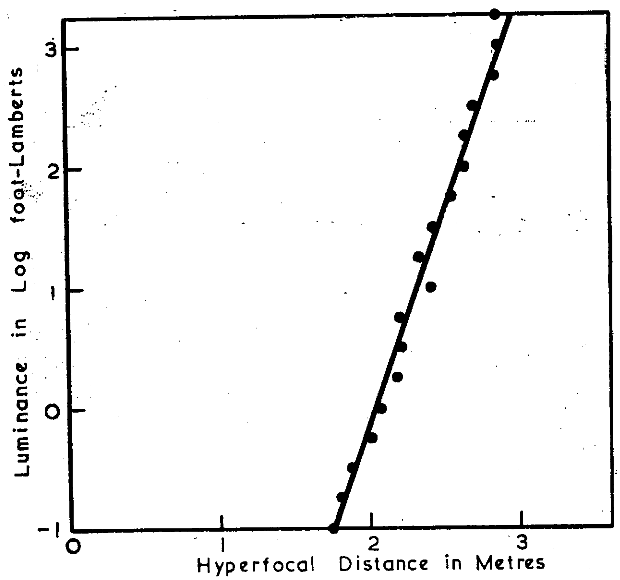

FIG. 2. — The effect of varying the luminance of the test field on the determination of the depth of field with a 3 mm diameter artificial pupil.

It can be seen that there is a linear relation between the log of the luminance and the hyperfocal distance. As expected, the higher the luminance the more readily does the observer detect out-of-focus blurring. Observations could not be carried out at luminance levels lower than 0.1 mL as the 10' diameter test spots could barely be detected below this level. The highest luminance which could be obtained with the apparatus was 3,000 mL, which is near the luminance of a piece of white paper viewed in full sunlight.

Lythgoe (1932) found an approximately linear relation between foveal visual acuity and the log of the luminance of the test object over this range of luminance. It thus seems probable that the results obtained here can be explained on the basis of change of retinal resolving power with luminance, although they cannot be accurately predicted from the results of Lythgoe. If this be true, then depth of field measurements should also vary with the contrast of the test objects against their background, for contrast is known to effect visual acuity measurements.

The effect of contrast on depth of field.

The results in this experiment were obtained while using a 3 mm diameter artificial pupil. The 10' spots were white and kept at a constant luminance of 100mL while the luminance of the background was varied. Contrast was expressed as follows:-

$$\text{Contrast} = \frac{\text{Test spot luminance} - \text{Background luminance}}{\text{Test spot luminance}}$$

The results are shown in figure 3.

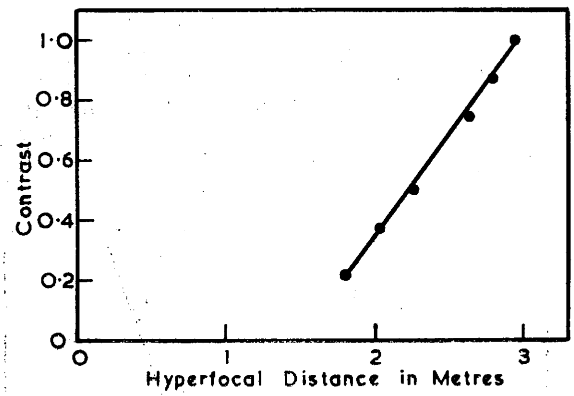

FIG. 3. — The effect of varying the contrast between the test objects and their background on the determination of the depth of field. Pupil diameter was 3 mm.

It can be seen from figure 3 that a linear relation is found between contrast and hyperfocal distance over the range tested. The greater the contrast the easier became the detection of out-of-focus blurring. Determination of the depth of field became difficult below a contrast of 0.2 as the test spots merged with the background.

The effect of pupil size on depth of field.

The relation between pupil size and depth of field has been investigated over the pupil range 0.75 to 7 mm diameter. Over this range the pupil area alters by a factor of 87 times, so that the retinal illumination alters by $10^{1.94}$. Reference to figure 2 will show that such a change of retinal illumination will have an appreciable effect on any estimate of depth of field. To isolate the effect of change of pupil size it is, therefore, necessary to keep retinal illumination constant. Strictly, the brightness of a photopic field varies only approximately with pupil area, for with large pupils the retinal direction effect diminishes the apparent brightness of light rays reaching the retina through the peripheral parts of the retina (Stiles and Crawford, 1933). Using the data published by Stiles and Crawford, the subjective brightness of the test field was held constant with change of pupil size by adjusting the neutral wedge immediately in front of the artificial pupil.

The effect of altering pupil size on the hyperfocal distance at constant subjective brightness is shown in figure 4. At 1 mm pupil diameter the luminance of the background was 100 mL.

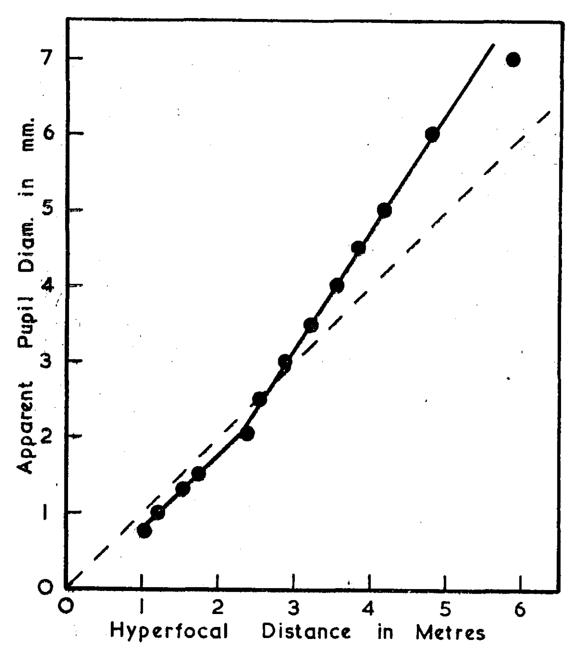

FIG. 4. — The effect of altering pupil size on the hyperfocal distance at constant retinal illumination. At 1 mm pupil diameter the luminance of the background was 100 mL.

It can be seen from figure 4 that as the pupil diameter increases the hyperfocal distance increases. Two straight lines of different gradient can be fitted to the results. If the eye behaves as a perfect optic system and obeys the laws of geometric optics these lines should on extension pass through the zero of the axis. Clearly they do not do so. As judged by eye, the interrupted line is the best straight line passing through the zero of the axes which can be fitted to the results. It represents the theoretical relation between pupil dimater and hyperfocal distance and corresponds to a disc of confusion approximately 1/1,000 th of the posterior nodal distance of the eye. The hyperfocal distance is found to be greater than that predicted by geometric optics at pupil diameters smaller than 2 mm and less than that predicted for pupil sizes larger than 2 mm.

The deviation of the results obtained with pupil diameters greater than 2 mm can readily be accounted for by the retinal direction effect. Stiles and Crawford (1933) demonstrated that a ray of light entering a peripheral portion of the pupil was less effective in stimulating the retinal cones than a ray of equal intensity entering by the centre of the pupil. Thus at wide pupil diameters the peripheral portions of the optical system of the eye do not contribute fully to the final visual perception. As these peripheral rays produce some of the blurring around an out-of-focus image formed on the retina, any diminution in their effective brightness will reduce the amount of blurring perceived. The effective pupil size could be defined as that size of pupil which would give rise to a given subjective brightness if there was no retinal direction effect. For example, according to the data of Stiles and Crawford a natural pupil of 6 mm diameter would have to be replaced with a pupil of 5.6 mm diameter to give the same subjective brightness as before in the absence of the retinal direction effect. The following formula has been devised by Martin (1954) to find the effective pupil size and is the one used in this thesis to correct the results.

$$R_e = \sqrt{\frac{1 - \exp(-0.105 R^2)}{0.105}}$$

Where R_e = effective pupil radius
R = pupil radius as measured through the cornea.

The results shown in figure 4 have been corrected for this effect and are shown in figure 5. The retinal direction effect is too small to influence the results obtained at pupil diameters less than 2.5 mm and they are not shown.

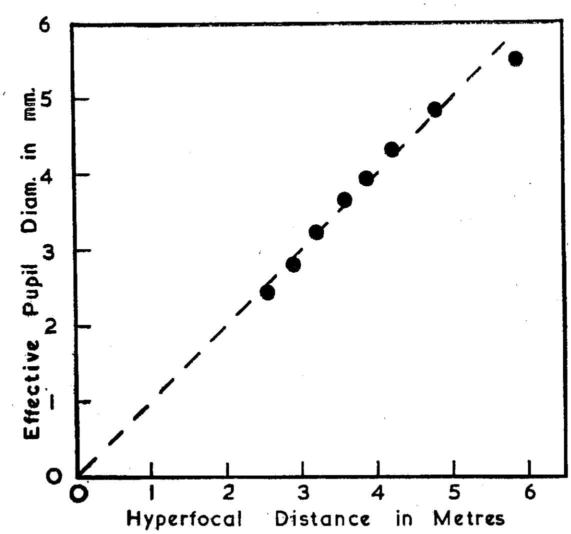

FIG. 5. — The results shown in figure 4 corrected for the retinal direction effect of STILES and CRAWFORD [18].

It can be seen that the corrected results agree closely with the predicted results. The results obtained with the 7 mm pupil (effective diameter 5.3 mm) does not fit so closely, but this may be due to the practical difficulty of centering the artificial pupil accurately on the dilated natural pupil.

The close agreement of the corrected results with the theoretical relation between pupil size and depth of field strengthens the hypothesis that the retinal direction effect influences out-of-focus blurring, but the agreement could be coincidental. The next experiment was designed to test the hypothesis more critically.

<u>The effect of colour on depth of field.</u>

The magnitude of the retinal direction effect has been found to vary with the wavelength of the light (Stiles, 1937). Thus, if the perception of blurring is influenced by this effect, the depth of field of the eye should also vary with the colour of the visual field at wide pupil apertures. To test this deduction the depth of field was determined by examining the test field through Ilford spectrum filters No. 600 to 609. The neutral density wedge was adjusted so that the apparent luminance of the field was the same for each wavelength (1 mL).

The results are shown in figure 6. The horizontal interrupted lines indicate the depth of field for white light at a luminance of 1 mL for the various pupil sizes used.

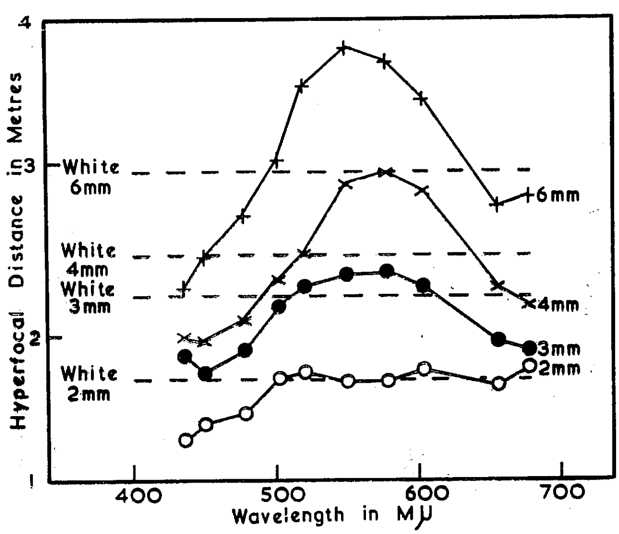

Fig. 6. — The effect of change of wavelength of the background on hyperfocal distance at pupil diameters of 2, 3, 4 and 6 mm. The horizontal interrupted line indicates the hyperfocal distance obtained with white light at these pupil sizes. All measurements made at a luminance of 1 mL.

With an artificial pupil diameter of 2 mm the depth of field between 500 and 690 mμ is fairly constant and close to the value for white light. Between 410 and 500 mμ the hyperfocal distance decreases, indicating that the eye is tolerating a greater degree of out-of-focus blurring.

However, the results obtained with a 6 mm diameter pupil are quite different. The hyperfocal distance for wavelength 550 mμ is greater than that for white light, indicating that the eye is more sensitive to out-of-focus blurring near to the middle of the visible spectrum.

With blue or red light, however, the hyperfocal distance is less than that for white light. Intermediate results are obtained with pupils of 3 an 4 mm diameter.

In figure 7 is plotted the effect of wavelength change on the retinal direction effect as obtained by Stiles (1937). The scale of the ordinate has been chosen to give a similar change in magnitude ~~as~~ to that shown in figure 6.

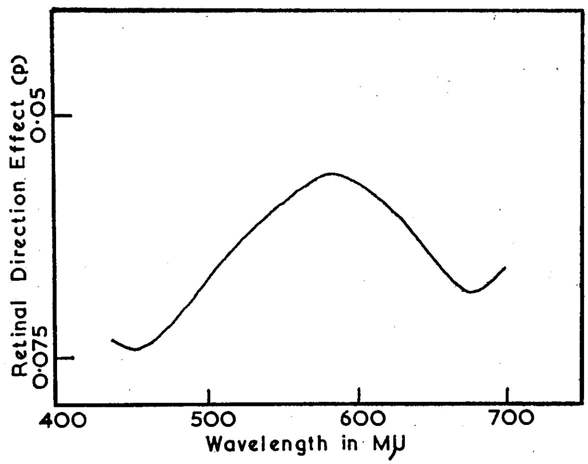

FIG. 7. — The relationship between the magnitude of the retinal direction effect and the wavelength of the test light. Redrawn from STILES (14). The scale of the ordinates has been chosen to give a similar change in magnitude to that shown in figure 6.

Comparison of figures 6 and 7 shows several points of similarity in the graphs. The wavelength which produces the minimum depth of field and the mimimum retinal direction effect is about 580 mμ. The short wave end of the spectrum produces a larger depth of field and a greater retinal direction effect than the long wavelength end of the spectrum. These similarities and the finding that the effect increases with increase in pupil size, further supports the conclusion that the retinal direction effect influences the perception of out-of-focus blurring. Closer agreement could not be expected as Stiles and Crawford have shown that some variation of the effect occurs between observers.

However, the change which occurs in the depth of field with wavelength cannot be entirely accounted for on the basis of the retinal direction effect. Inspection of figure 6 shows that even with a 2 mm pupil the hyperfocal distance decreases progressively with wavelengths less than 500 mμ. At this small pupil size the retinal direction effect is too slight to account for the change found at the blue end of the spectrum. The most likely explanation of this deviation is a decrease in retinal resolving power with short wavelengths. To test this explanation, the vernier visual acuity was determined at various wavelengths at a luminance of 1 mL.

The results are shown in figure 8.

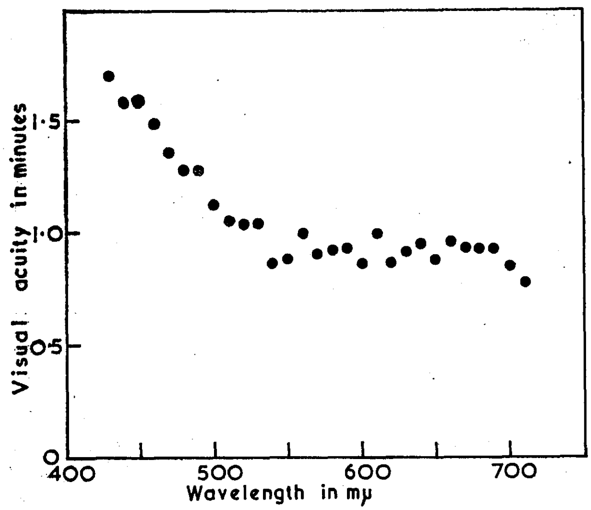

FIG. 8. — The variation of vernier visual acuity with wavelength. All measurements made at luminance of 1 mL. Chromatic difference of focus corrected with achromatising lens.

It can be seen that at this luminance the vernier acuity decreases rapidly from 520 to 430 mμ. It thus seems likely that some of the decrease in hyperfocal distance with shorter wavelengths, as shown in figure 6, is due to alteration in retinal resolving power and that it is not due entirely to the retinal direction effect.

A further point of interest arises from the results shown in figure 6. It is clear that at larger pupil sizes the depth of field with light of wavelength about 560 mμ is less than that obtained with white light of the same luminance.. As these measurements were made with fairly narrow band colour filters, any colour fringes around the retinal image due to chromatic aberration would be eliminated. But the fringes would be present in the measurements made with a white background. The next experiment was therefore designed to test if the elimination of chromatic aberration modifies the determination of the depth of field.

The effect of chromatic aberration on the depth of field.

It has long been known that the normal human eye is myopic to light from the blue end of the spectrum and hypermetropic to light from the red end. The magnitude of this chromatic difference of focus is considerable and is shown for the author's left eye in figure 9.

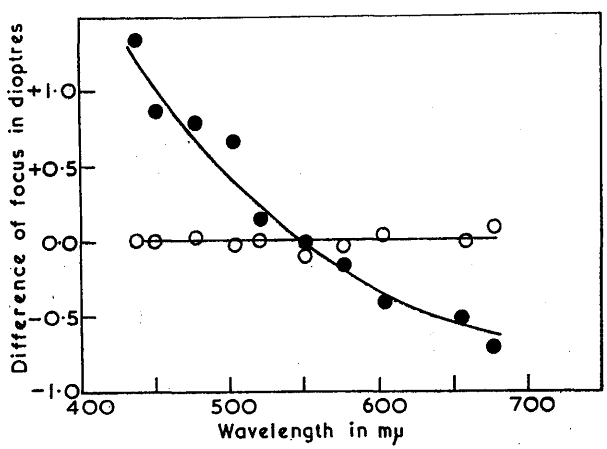

FIG. 9.— ● chromatic difference of focus of author's left eye. ○ chromatic difference of focus after correction with the THOMSON and WRIGHT lens.

The magnitude of the chromatic difference of focus agrees well with the estimates of Hartridge (1947) and Ivanoff (1947). The chromatic difference of focus does not vary with pupil size, but the size of the coloured fringes around an image does decrease with diminution of pupil size. That is, lateral chromatic aberration is modified by pupil aperture but not chromatic difference of focus.

The simplest and most effective way of eliminating chromatic aberration is to use monochromatic light but, as may be seen from the previous experiments, this would involve also a change in the effective pupil size due to the retinal direction effect. To overcome this complication an achromatizing lens designed by Thomson and Wright (1947) was used. Due to the small dimensions of this lens, a 3 mm diameter artificial pupil was the largest that could be used. It can be seen from figure 9 that this lens eliminates the chromatic difference of focus in the left eye of the author. It does not, however, entirely abolish the colour fringes around an image for it incompletely corrects the chromatic difference of magnification, but this will be of small magnitude if the lens is placed close to the eye and is correctly centred.

The effect of eliminating the chromatic difference of focus on the depth of field in 4 subjects is shown in table 3. It can be seen in all cases that the depth of field expressed in dioptres is diminished when the subjects use the achromatizing lens. That is, the subject perceives out-of-focus blurring with greater ease when the chromatic fringes around an image are diminished.

Table 3.

Subject	Depth of focus in dioptres with 3 mm pupil: Without achromatic lens.	With achromatic lens.
F. W. C.	± 0.34	± 0.31
A. M. C.	± 0.43	± 0.36
H. C.	± 0.56	± 0.51
T. C. D. W.	± 0.38	± 0.35

Results obtained with other subjects.

With the exception of some results shown in table 3, all the findings were obtained by the author, who took particular care to correct an astigmatic error of 0.75 dioptre. His corrected visual acuity measured with a broken C test was 6/4. The experiments were particularly fatiguing as accurate judgement of presence or absence of blurring requires careful adjustment of the apparatus. For this reason it has not yet been possible to repeat all the experiments in full with other subjects, but a number of limited confirmatory experiments have been carried out and some of the results are shown in table 4.

Table 4.

Subject.	Depth of focus with 3 mm pupil at 1,000 mL.	Depth of focus with 3 mm pupil at 1 mL.
F. W. C.	± 0.33 D	± 0.52 D.
H. M. C.	± 0.45	± 0.53
A. M. C.	± 0.43	± 0.62
A. S.	± 0.54	± 0.63
H. S.	± 0.49	-
T. C. D. W.	± 0.38	-
T. A. S. B.	± 0.45	-

It can be seen that the author (F.W.C.) was able to detect out-of-focus blurring with greater ease (0.33 D) than any of the other subjects. This may well be due to practice and familiarity with the apparatus. It may be significant that the next lowest result (0.38 D) was obtained with subject T.C.D.W., who has had extensive experience of this type of observation.

DISCUSSION.

It is clear from these results that no absolute value can be given for the depth of field of the human eye, for the magnitude depends upon such factors as the luminance, contrast and colour of the test target and also upon the experience of the subject.. Throughout this investigation the limits of the depth of field have been determined by finding the threshold of perception of the blurring of the margins of a 10' black disc on a bright background. This type of test object was used to permit simultaneous comparison of similar test objects placed at the far and near point of the depth of field with test objects known to be near the conjugate focus of the retina. The size of the test object was arbitrarily chosen to be 10' after a few preliminary tests had shown that smaller discs were difficult to detect at low luminances and contrasts. It is probable that test objects of different

different size and shape would give different values for the depth of field, but little different information of physiological interest would accrue from these observations.

There are good grounds for believing that the method used in this investigation is a sensitive one which gives low values for the depth of field. Von Bahr (1952) has used a test involving the measurement of vernier visual acuity to determine the limits of the depth of field and has obtained values substantially higher than those of the present investigation; furthermore, the limits of his experimental error appear to be large and he was unable to demonstrate a consistent change of depth of field with colour. Brickley and Ogle (1953) have tested several methods and conclude that a test based on the recognition of blurring of a point source of light was a more critical method than a test involving measurement of visual acuity. Oshima (1958) on the other hand has recently published a paper giving values for the depth of field some 10 to 15 times smaller than found in this investigation. His method was to have two planes at different distances, one plane being fixed and the other moveable. By means of mirrors these planes were mixed so that a sharp boundary line formed where the planes met. It is difficult to understand why this paticular type of target presentation should be so much more sensitive to blurring to the extent of at least a factor of 10. From his data it is possible to calculate that the blur of the boundary line became apparent when its breadth was subtending an angle of only 12" of arc.

In this investigation, the lowest value obtained under optimum conditions of luminance and contrast for the depth of field is about ± 0.3 D for a 3 mm diameter pupil. If such an eye is assumed to be a perfect optical system without aberrations, a point source would subtend a blur disc approximately 3' in diameter when placed at the limits of the depth of field. This value is about 2 to 3 times greater than the figure conventionally used for calculating the depth of field by means of geometric optics. On the other hand, the data of Oshima is about 5 times less than the conventional figure.

Fry (1955) appears to be the only worker who has calculated the depth of field by considering the out-of-focus image in terms of diffraction and wave theory. He calculated that, when the eye is out of focus, the geometrical image can be regarded as a close approximation to the physical image determined by wave theory.

Several factors appear to contribute to the relative insensitivity of the eye to out-of-focus blurring. Firstly, the results of this study indicate that when the chromatic aberration of the eye is diminished the observer can detect out-of-focus blurring with greater ease. Ohman (1949) also noted this effect and furthermore claimed that the depth of field was increased if a lens was used which increased the amount of aberration present in the normal eye. However, von Bahr (1952) was unable to confirm this finding using Ohman's own hyperchromatizing lens. Fry (1955) calculated that the depth of focus of the eye should be greater with white light than with monochromatic light. Now in this thesis the results were obtained by modifying the chromatic aberration of the eye by means of monochromatic light, and by the use of an achromatizing lens, and also by means of a small pupil. These three methods all diminish the size of chromatic aberration fringes around an image although they have varying effects on the chromatic difference of focus and on the chromatic difference of magnification of the eye. Thus it may be concluded that it is the fringes normally found around a retinal image which increase the threshold of perception of out-of-focus blurring.

The retinal direction effect of Stiles and Crawford also helps to increase the depth of field of the eye, especially when the pupil is large. The normal range of pupil diameter that will occur under photopic viewing conditions is 2 to 6 mm. Over this range the depth of field was found to vary from ± 0.43 to ± 0.21 D., that is, a change by a factor of two approximately. But for the retinal direction effect this change would be by a factor of three. In calculations to determine the depth of field it is therefore necessary to use not the apparent size of the pupil as viewed through the cornea, but the effective pupil diameter which may be obtained from the data of Stiles and Crawford.

The same qualification applies to an artificial pupil if it acts as the entrance pupil of the eye or to the limiting pupil of an optical instrument.

Fletcher (1951) appears to have realised that the retinal direction effect should be considered when discussing the depth of focus, for he states:-

"The Stiles-Crawford effect has a bearing on practical applications of ocular depth of focus. The eye probably ignores some of the blurred area of a retinal image because of the larger angles of incidence associated with blurring. A useful range of tolerance may be extended thus to astigmatic errors, particularly to simple astigmatism."

Although he does not present any experimental results to substantiate his statement the results presented in this thesis do confirm his deduction.

All human eyes have some degree of spherical aberration although there are large individual variations in its magnitude. At wide pupil apertures this aberration might affect depth of field measurements. However, it has not been necessary to postulate the operation of this factor to account for the results in this investigation.

For practical guidance table 5 is presented. To construct this table it has been assumed that the eye can just detect a variation of ± 0.3 D with a 3 mm pupil under conditions of high luminance and high black and white contrast. The values for other pupil sizes have been corrected for the retinal direction effect using the factors given by Martin (1954). No correction has been made for the effects of chromatic aberration or variations in retinal illumination.

TABLE #5

Pupil diameter in mm.	Depth of focus	Depth of field, when focussed on :		
		Infinity	Hyperfocal distance	25 cm
1	±0.85	α to 1.18 m	α to 0.59 m	31.8 to 20.6 cm
2	±0.44	α to 2.27 m	α to 1.13 m	28.1 to 22.5 cm
3	±0.30	α to 3.33 m	α to 1.67 m	27.0 to 23.3 cm
4	±0.24	α to 4.17 m	α to 2.08 m	26.6 to 23.6 cm
5	±0.20	α to 5.00 m	α to 2.50 m	26.3 to 23.8 cm
6	±0.18	α to 5.56 m	α to 2.28 m	26.2 to 23.9 cm
7	±0.16	α to 6.25 m	α to 3.12 m	26.0 to 24.0 cm
8	±0.15	α to 6.67 m	α to 3.33 m	26.0 to 24.1 cm

Depth of field if the eye based on the detection of ± 0.3 D with a 3 mm diameter pupil and corrected for the retinal direction effect.

ACKNOWLEDGEMENTS

The optical apparatus used in this investigation was kindly supplied by the W. H. Ross Foundation (Scotland). I would like to thank Professor W. D. Wright for the loan of the achromatizing lens and for interest in this work. My thanks are due to Dr W. S. Stiles for his interest and criticism of the results of this work.

SUMMARY.

1. A simple but accurate method of measuring the depth of focus of the human eye is described.

2. At a fixed pupil size the hyperfocal distance was found to increase directly with the log of the background luminance over the photopic range.

3. If the luminance and pupil size is held constant the hyperfocal distance is found to vary linearly with the contrast.

4. If the contrast and the retinal illumination is held constant, the depth of field varies approximately inversely with pupil size.

5. With pupil diameters greater than 2.5 mm the observed deviation of the hyperfocal distance from theoretical expectation can be accounted for by the operation of the retinal direction effect of Stiles and Crawford.

6. Further evidence that the retinal direction effect modifies depth of field has been obtained by measurement with fields of different colour but similar luminance.

7. Correction of the chromatic aberration in the eye by means of an achromatizing lens decreases depth of field. The reason for this appears to be the reduction of the coloured fringes around a retinal image rather than the decrease of the chromatic difference of focus produced by the achromatizing lens.

8. The minimum estimate for depth of field obtained in these experiments under optimum conditions of contrast and luminance was about $\pm$ 0.3 D at a pupil diameter of 3 mm.

9. The results obtained by other workers in this field are discussed in the light of the present results.

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